Seasonal Geocenter Motion from Space Geodesy and Models

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Geocenter Motion Definition

IERS2010 Conventions:

C) *Geocentric positions*

The ITRF origin should be considered as the mean Earth center of mass, averaged over the time span of the SLR observations used and modeled as a secular (linear) function of time. If an instantaneous geocentric position $\vec{X}$ is required, it should be computed as

$$\vec{X} = \vec{X}_{ITRF} - \vec{O}_G, \tag{4.16}$$

where $\vec{O}_G$ represents the geocenter motion in ITRF (vector from the ITRF origin to the instantaneous center of mass) $<^2>$.

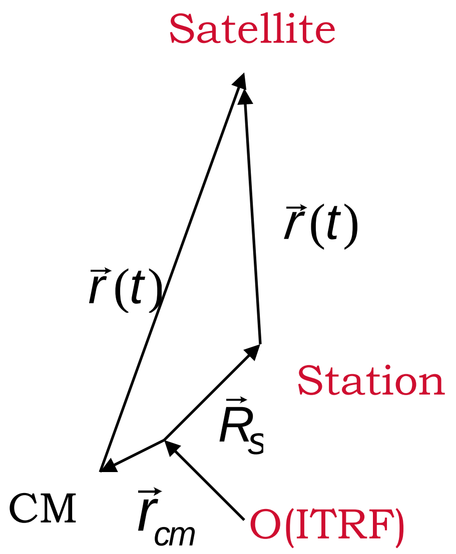
By definition, ITRF does not include seasonal variations between the mean and instantaneous center of mass; these must be included as a correction

$$\vec{R}_s(t) = \vec{R}_{so} + (t - t_o)\vec{V}_s + \Delta\vec{R}_s(t)\ (tides,\ ocean\ loading, pole\ tides,\ etc.)$$

IERS conventions include tidally coherent geocenter motion, but not non-tidal; non-tidal variations dominate the annual geocenter motion.

‘Dynamical’ Approach to Determine Geocenter Motion

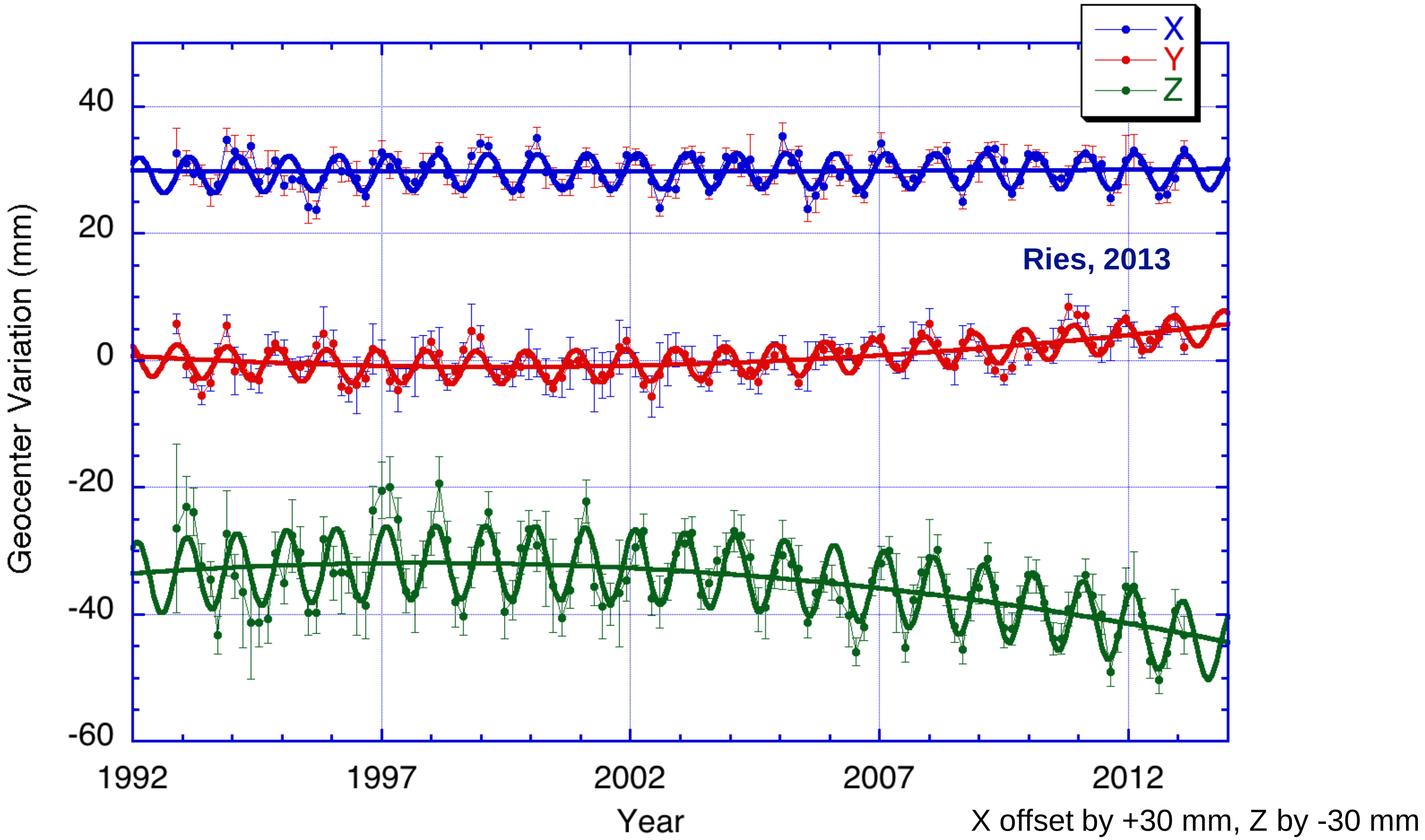
- Satellites orbit about the center of mass of the entire Earth system (solid Earth, oceans and atmosphere).
- Geocenter motion vector $\vec{r}_{cm}$ can be estimated simultaneously with the orbit.
- This is identical to estimating degree-1 gravity harmonics (as long as a Coriolis-type correction is included to account for the fact that the geocentric frame origin is no longer an inertial point [Kar, 1997]).
- Degree-1 mass redistribution (load) and geocenter motion tend to be used interchangeably.



$$\vec{r}_{cm} = a_e(C_{11}, S_{11}, C_{10})$$

Geocenter Motion from SLR (1)

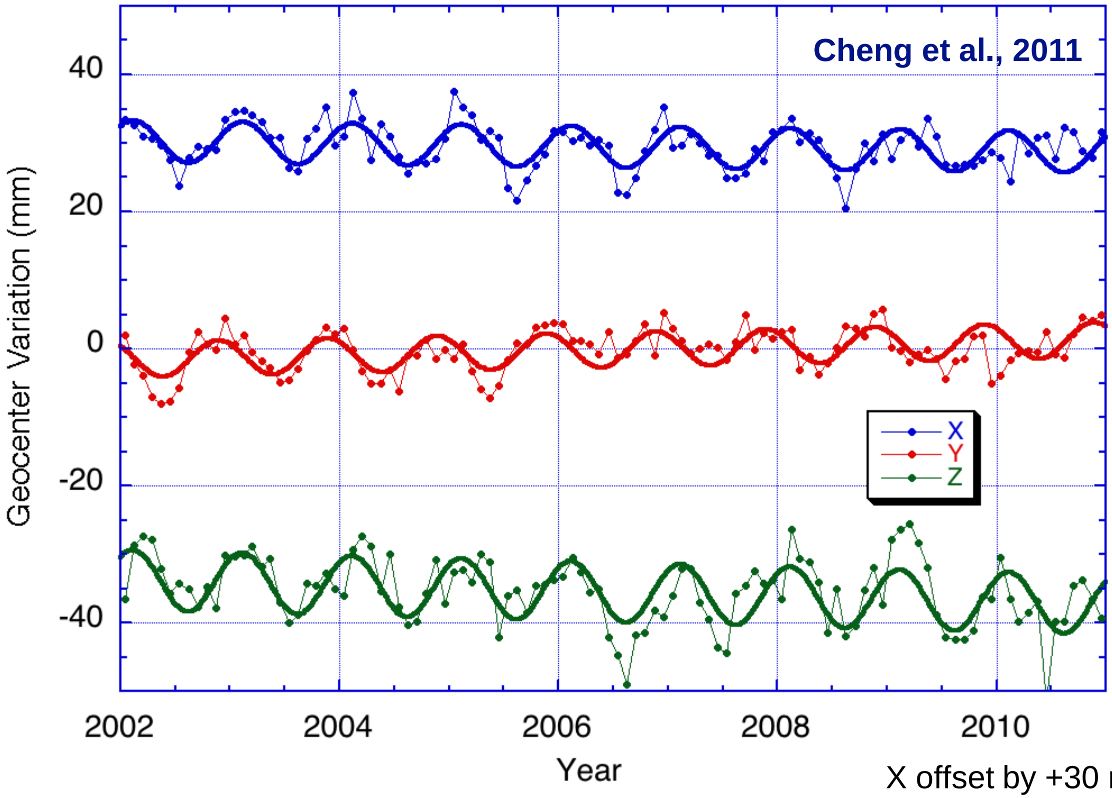
60-day estimates of geocenter from LAGEOS-1/2
SLRF2005/LPOD2005 station coordinates



X (amp)	X (phase)	Y (amp)	Y (phase)	Z (amp)	Z (phase)	Reference (comments) (phase is in degrees)
2.8	47	2.6	324	5.8	34	Ries, 2013 (60-day estimates; 1993-2012)
2.9	43	2.6	323	6.0	37	Ries, 2013 (30-day estimates; 1993-2012; estimate 2x2 gravity)

Geocenter Motion from SLR (2)

Monthly estimates of geocenter from 5 satellites
SLRF2005/LPOD2005, AOD applied, estimate monthly 5x5 gravity field



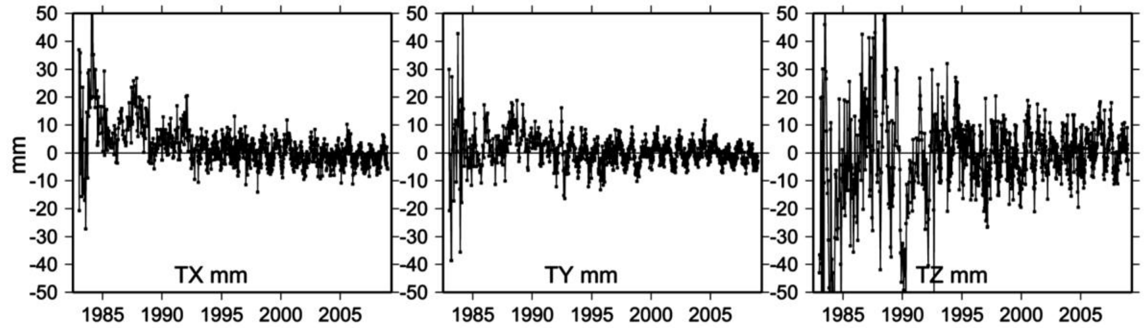
X offset by +30 mm, Z by -30 mm

X (amp)	X (phase)	Y (amp)	Y (phase)	Z (amp)	Z (phase)	Reference (comments) (phase is in degrees)
2.7	35	2.8	309	5.2	25	Cheng et al., 2010 (weekly solutions, estimating 5x5 gravity, 1993-2010)
3.0	43	2.6	321	4.4	42	Cheng et al., 2010 (monthly solutions, estimating 5x5 gravity, 2002-2010)

‘Kinematic’ Approach

Stack time series of loosely-constrained frame estimates

Z. Altamimi et al.



Altamimi et al., 2010

Fig. 4 Weekly translation components of the SLR ILRS solution with respect to ITRF2008, in millimeter along the *X*, *Y* and *Z*-axes: *left*, *middle* and *right*, respectively

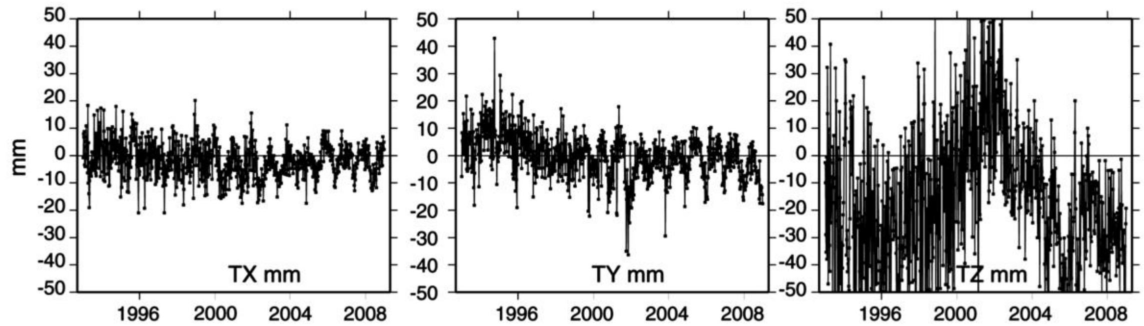
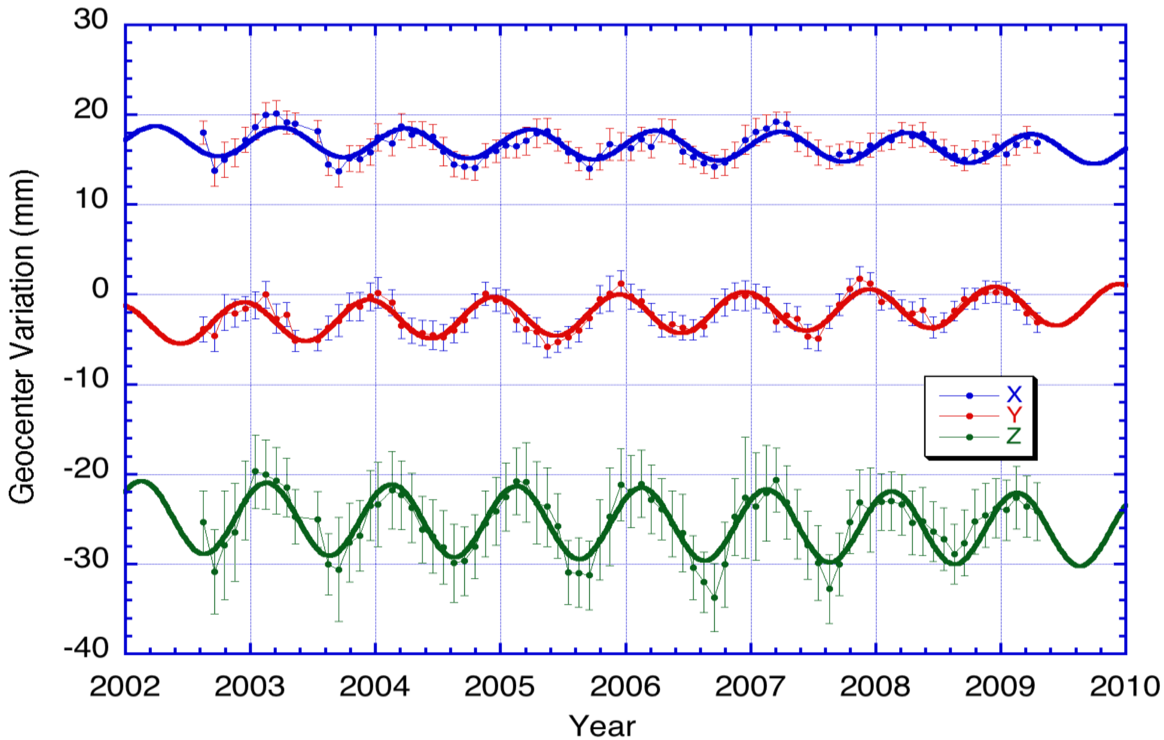


Fig. 5 Weekly translation components of the DORIS IDS-3 solution with respect to ITRF2008, in millimeter along the *X*, *Y* and *Z*-axes: *left*, *middle* and *right*, respectively

X (amp)	X (phase)	Y (amp)	Y (phase)	Z (amp)	Z (phase)	Reference (comments) (phase is in degrees)
2.6	42	3.1	315	5.5	22	Altamimi et al., 2010 (ILRS contribution to ITRF2008)

‘Global Inversion’ Approach

Estimate degree-1 deformation from GPS, using other information (GRACE, Ocean bottom pressure, etc.) to remove load signal above degree 1



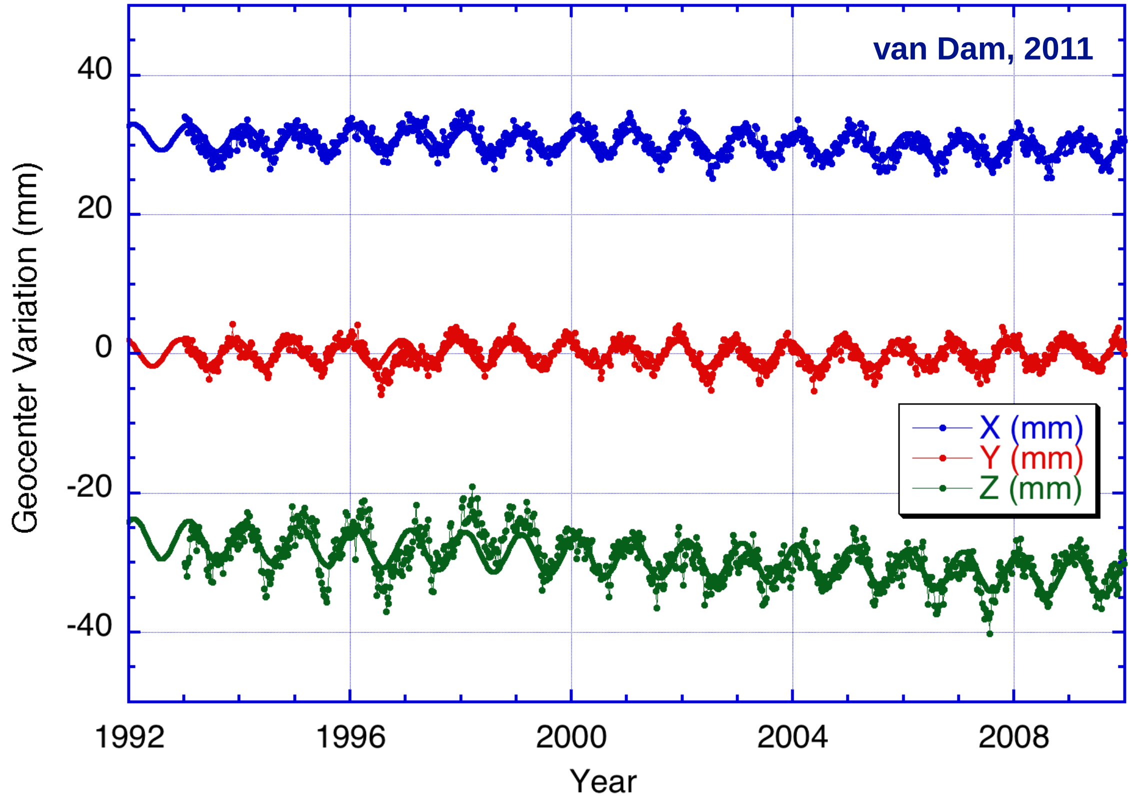
Wu et al., 2010

X (amp)	X (phase)	Y (amp)	Y (phase)	Z (amp)	Z (phase)	Reference (comments) (phase is in degrees)
1.9	42	3.2	328	3.6	25	Wu, 2006
2.0	21	2.6	334	3.6	24	Jansen et al., 2009
1.8	49	2.7	325	4.2	31	Wu et al., 2010
2.0	62	3.5	322	3.1	19	Rietbroeck et al., 2011 (updated June 2011)

Geophysical Models

Geophysical models of atmosphere, ocean, and hydrology can provide degree-1 mass redistribution and predict the corresponding geocenter motion after accounting for the load deformation

(models may not fully capture complete mass redistribution, leading to smaller seasonal variations)



X (amp)	X (phase)	Y (amp)	Y (phase)	Z (amp)	Z (phase)	Reference (comments) (phase is in degrees)
1.8	36	2.1	332	2.3	24	Chen, 2008
2.1	28	2.1	338	2.7	48	Coullilieux et al., 2009 (Forward model, NCEP, LaDWORLD-Frasier, ECCO OBP)
1.9	34	1.9	337	2.8	35	van Dam, 2011 (NCEP, ECCO, GLDAS, no arctic)

Ensemble of ‘Reasonable’ Estimates*

Geodetic observations	X (amp)	X (phase)	Y (amp)	Y (phase)	Z (amp)	Z (phase)	Reference (comments) (phase is in degrees)
SLR (L1/L2)	2.2	59	3.2	299	2.8	45	Eanes et al., 1997; Chen et al., 1999
SLR/DORIS/GPS	2.9	58	3.7	304	4.5	3	Montag, 1999
SLR	2.1	47	2.0	322	3.5	42	Bouille et al., 2000 (errors estimated to be 0.5-1.5 mm for amplitudes)
Topex/Poseidon (SLR/DORIS)	1.8	41	2.9	320	2.4	37	Eanes & Ries, 2000
SLR (L1/L2)	2.6	32	2.5	305	3.3	35	Creteaux et al., 2002
SLR (L1/L2)	1.3	45	2.2	321	2.6	31	Eanes, 2005 (12-year series of weekly solutions; scale also adjusted)
GPS	2.1	42	3.2	343	3.9	77	Lavallée et al., 2006 (errors estimated to by 0.5-0.8 mm and ~20° phase)
GPS loading + GRACE + OBP	1.9	42	3.2	328	3.6	25	Wu, 2006
SLR (ILRS)	2.7	45	3.8	327	3.6	4	Collilieux et al., 2009 (translation model; no scale)
SLR (ILRS)+GPS+OBP	2.4	32	2.6	322	5.3	23	Collilieux et al., 2009 (translation model estimated with inverse loading model)
SLR (ILRS)+loading model	3.7	34	1.8	324	3.7	34	Collilieux et al., 2009 (translation model estimated with forward loading model)
GPS + OBP	1.3	6	3.0	338	4.6	23	Coullilieux et al., 2009 (Inverse model, GPS+OBP)
SLR(ILRS)+GPS	2.5	19	3.2	327	3.4	17	Collilieux et al., 2009 (use GPS to correct for loadingl)
GPS loading + GRACE	2.0	21	2.6	334	3.6	24	Jansen et al., 2009
GPS loading + GRACE + OBP	1.8	49	2.7	325	4.2	31	Wu et al., 2010
SLR (ILRS)	2.6	40	3.1	315	5.5	22	Altamimi et al., 2010 (ILRS contribution to ITRF2008)
SLR (5 satellites)	2.7	40	2.8	323	5.2	30	Cheng et al., 2010 (weekly estimates of 5x5 gravity and geocenter, 1993-2010)
SLR (5 satellites)	2.9	35	2.6	306	4.2	44	Cheng et al., 2010 (monthly estimates of 5x5 gravity and geocenter, 2002-2010)
GPS loading + GRACE + OBP	2.0	62	3.5	322	3.1	19	Rietbroeck et al., 2011 (updated June 2011)
GRACE+Ocean Model	2.2	43	3.0	333	2.7	42	Swenson, Chambers & Wahr, 2008 (GRACE + OMCT) (updated 2012)
SLR (L1/L2)	2.9	43	2.6	323	6.0	37	Ries, 2013 (30-day estimates; 1993-2012; estimate 2x2 gravity)
SLR (L1/L2)	2.8	47	2.6	324	5.8	34	Ries, 2013 (60-day estimates; 1993-2012)
Mean (mm)	2.3	40	2.9	322	4.0	31	
Stdev (mm)	0.6	13	0.5	11	1.1	15	

* “reasonable” arbitrarily defined as realistic estimates in all 3 coordinates

Selected Geodetic Estimates and Models

Selected geodetic estimates							
Geodetic observations	X (amp)	X (phase)	Y (amp)	Y (phase)	Z (amp)	Z (phase)	Reference (comments) (phase is in degrees)
SLR (ILRS)+GPS+OBP	2.4	32	2.6	322	5.3	23	Collilieux et al., 2009 (translation model estimated with inverse loading model)
SLR (ILRS)	2.6	42	3.1	315	5.5	22	Altamimi et al., 2010 (ILRS contribution to ITRF2008)
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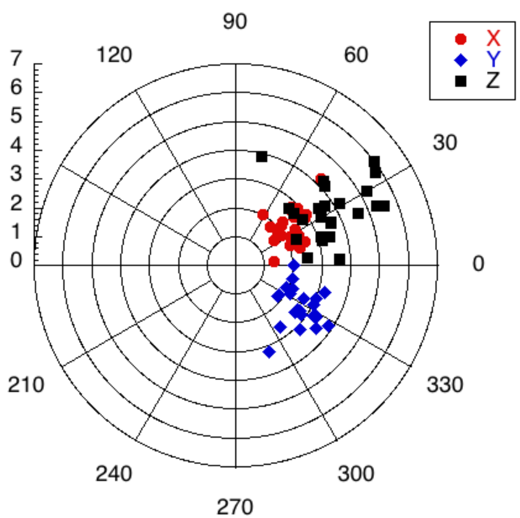
GPS loading + GRACE + OBP	2.0	62	3.5	322	3.1	19	Rietbroeck et al., 2011
Mean (mm)	2.3	41	2.8	323	4.7	27	
Stdev (mm)	0.4	13	0.3	6	1.1	6	

Geophysical model predictions	X (amp)	X (phase)	Y (amp)	Y (phase)	Z (amp)	Z (phase)	Reference (comments) (phase is in degrees)
Geophysical models	2.4	26	2.0	360	4.1	42	Chen et al., 1999
Geophysical models	1.6	34	1.8	326	3.1	16	Bouille et al., 2000
Geophysical models	4.2	46	3.2	291	3.5	35	Dong et al., 2003
Geophysical models	2.3	16	2.0	347	3.4	30	Moore & Wang, 2003 (CDAS-1 for land water)
Geophysical models	1.8	36	2.1	332	2.3	24	Chen, 2008
Geophysical models	2.1	28	2.1	338	2.7	48	Coullilieux et al., 2009 (Forward model, NCEP, LaDWORLD-Frasier, ECCO OBP)
Geophysical models	1.9	34	1.9	337	2.8	35	van Dam, 2011 (NCEP, ECCO, GLDAS, no arctic)
Mean (mm)	2.3	31	2.2	333	3.1	33	
Stdev (mm)	0.9	9	0.5	22	0.6	11	

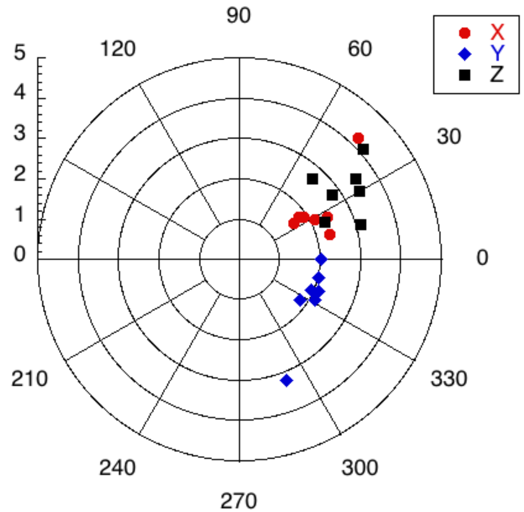
Phases agree well, but amplitudes from models generally smaller than geodetic estimates for Y and Z
GPS-based amplitudes for X and Z generally smaller than from SLR

Annual Geocenter Motion Estimates

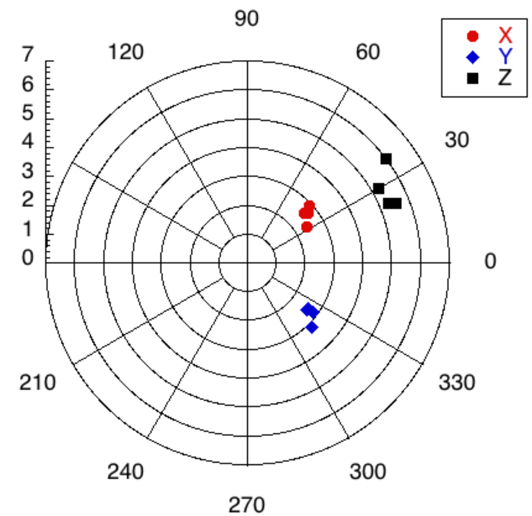
All Geodetic Estimates and Models



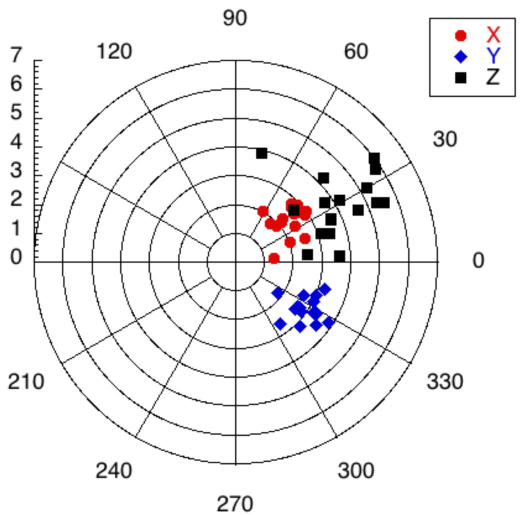
Geophysical models



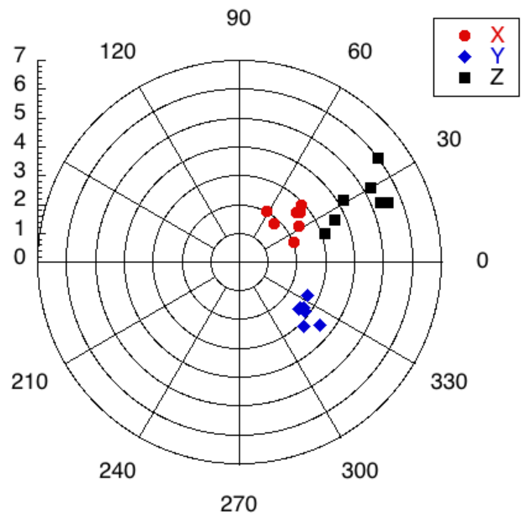
SLR-only Estimates



Geodetic Estimates



Selected Geodetic Estimates



"Climatological model"
SLR-only; all four span 15 or more years

X (amp)	X (phase)	Y (amp)	Y (phase)	Z (amp)	Z (phase)
2.7	39	2.8	321	5.5	28
0.2	5	0.2	4	0.4	7

Need for an Annual Geocenter Model

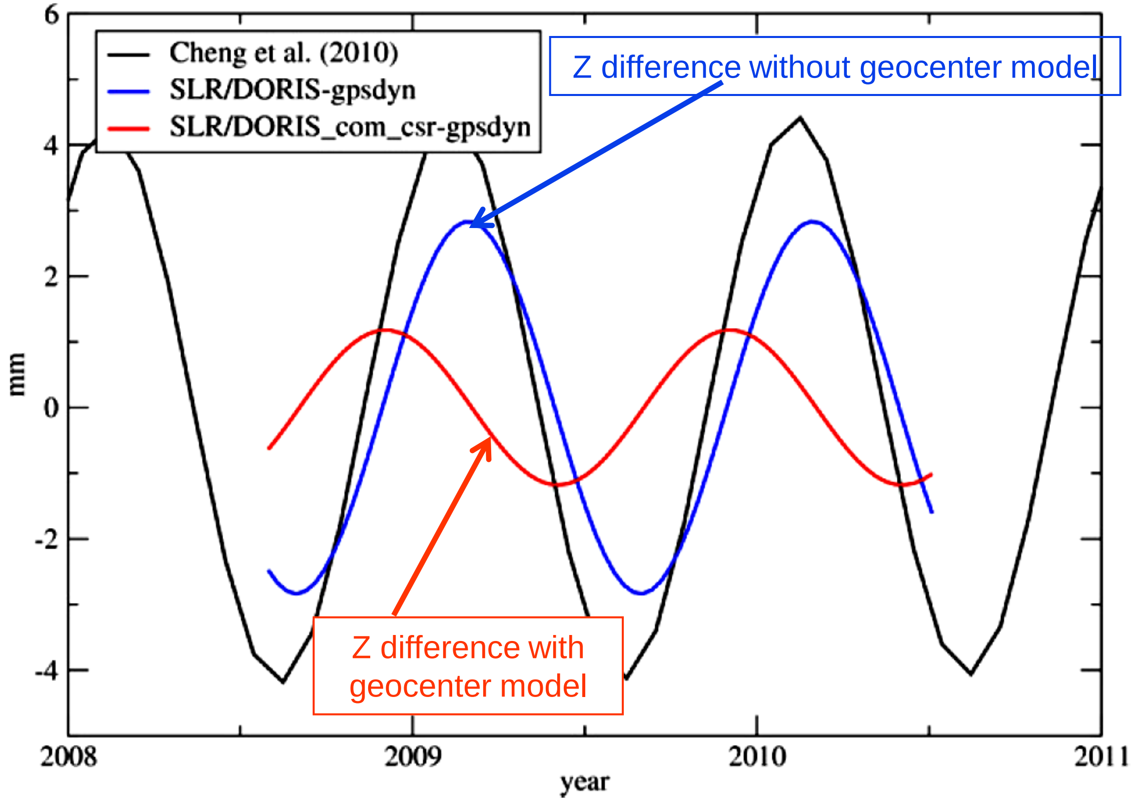
- Annual geocenter (or degree-1) represents major mass redistribution
- Depending on orbit determination tracking used, lack of a model can create artificial seasonal variations in regional and global sea level

Jason-2 orbit comparisons between GPS-based and SLR-DORIS-based orbits exhibit seasonal variation in Z *

Adding geocenter motion model reduces systematic difference (Melachroinos et al., 2013)

Effect on orbit is not 1 for 1, but closer to 0.7 for T/P and Jason orbit

*I speculate that GPS-based orbits are somewhat 'whitened' by larger but more random GPS orbit errors, while SLR/DORIS orbits are more rigidly tied to the TRF, which does not have a model for annual geocenter

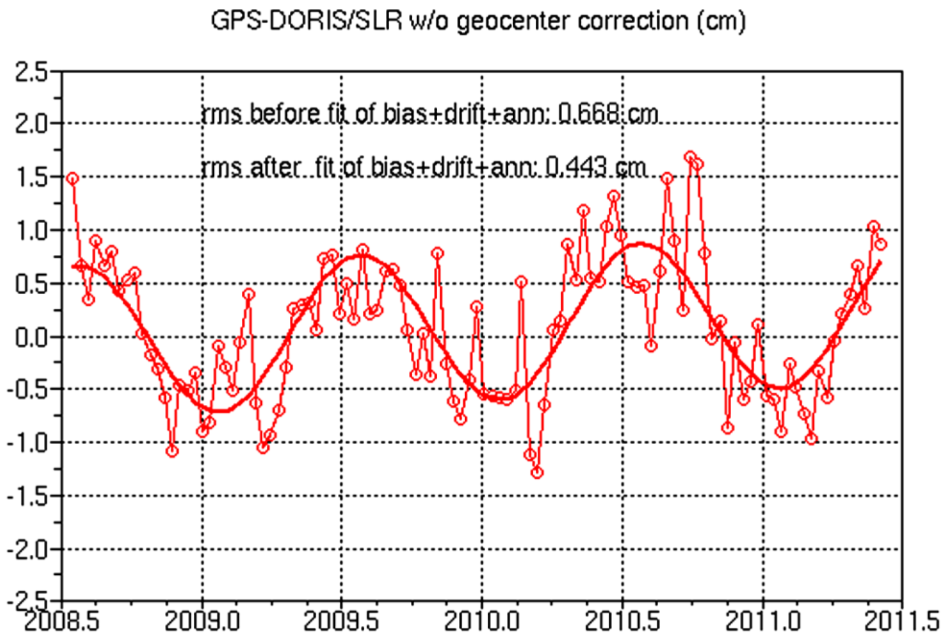


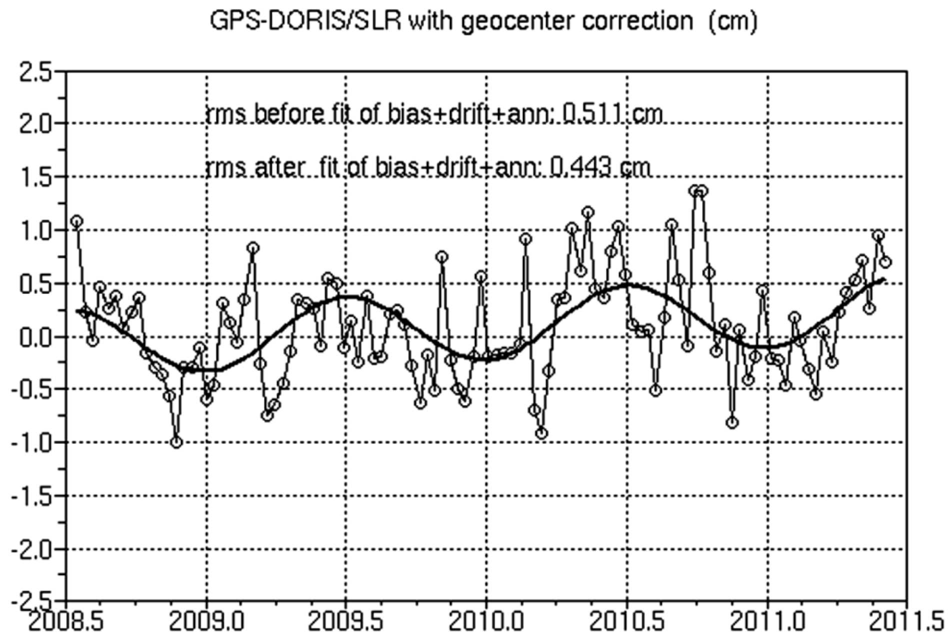
Another Example

Jason-2 orbit comparisons between GPS-based and SLR-DORIS orbits exhibit seasonal variation in Z that are reduced with a model (Cerri, 2011, personal communication)

Cerri used 4.2 mm for annual Z; more recent SLR estimates suggest something closer to 6 mm, which looks like it would have reduced the differences further

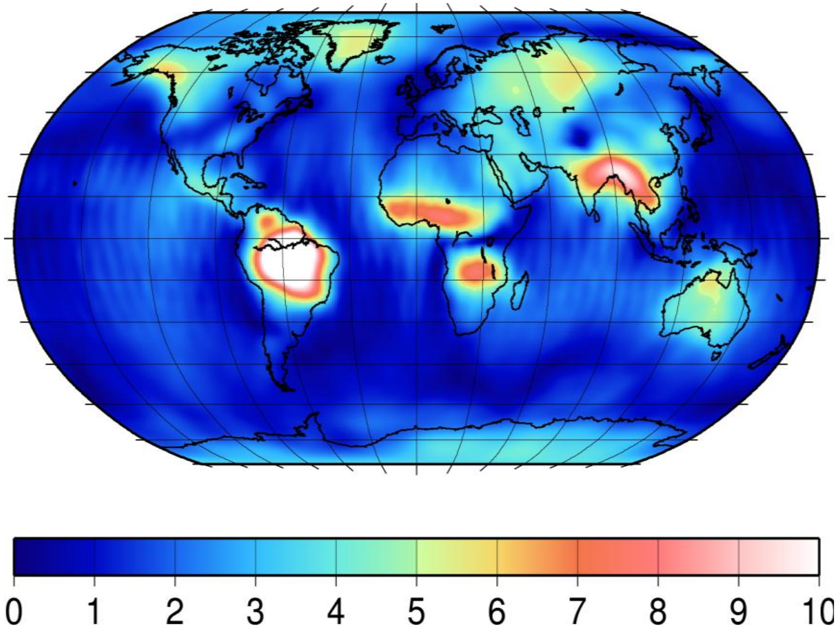
We should expect to get consistent orbits regardless of technique; geocenter motion model is essential for this



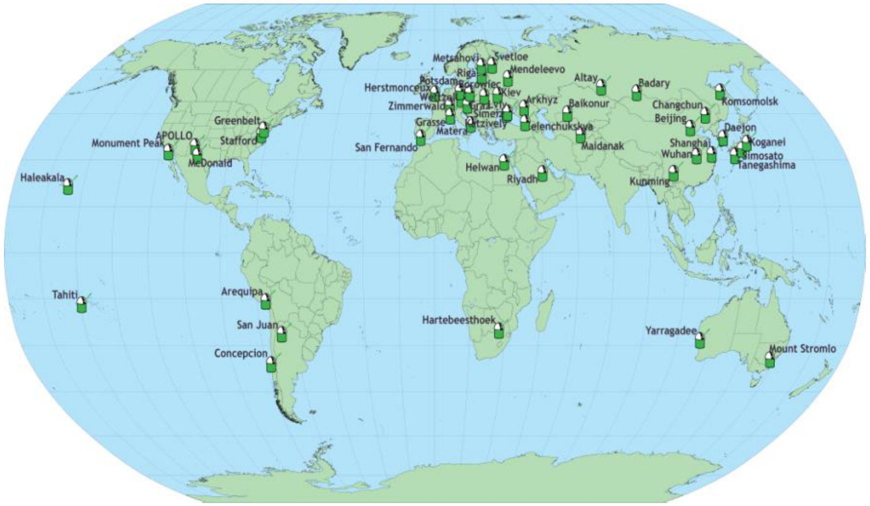


What is effect of higher degree loading?

- Geocenter translation estimates from SLR will be affected by local (higher-degree) loading since the SLR network is not globally dense
- Effect is minimized for SLR due to stations being located in generally benign mid-latitudes



Annual vertical deformation from GRACE (mm)
(horizontal is sub-mm at mid-latitudes)

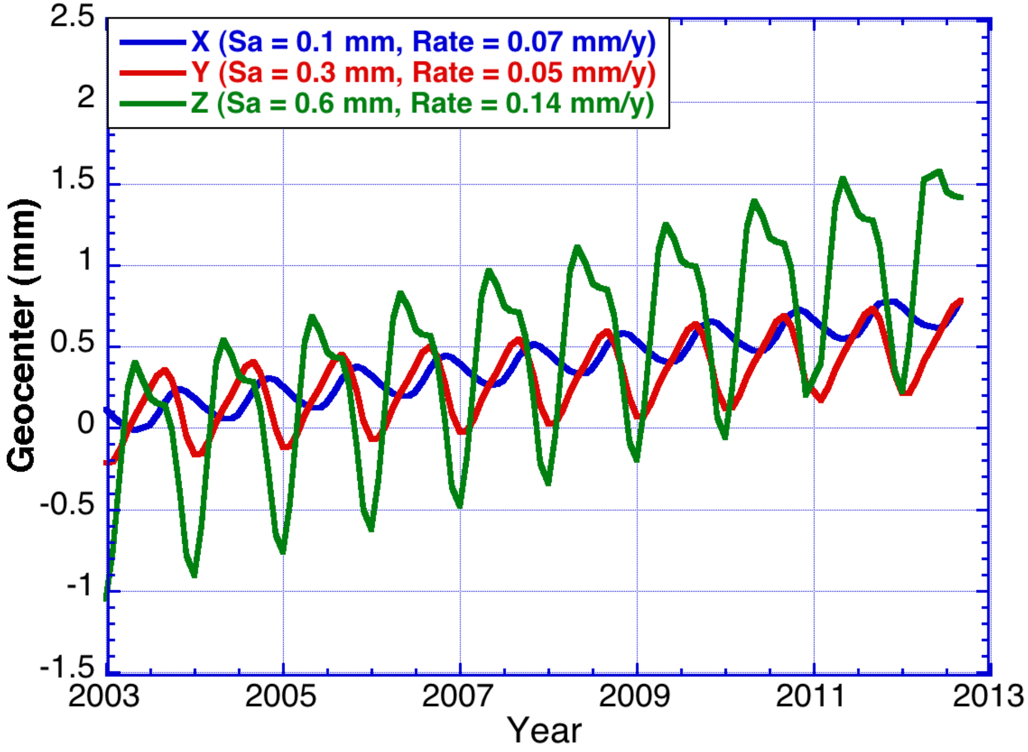


ILRS network

Effect of higher degree loading

- Higher degree loading (based on GRACE estimates) results in an effect on the translation estimates that is not insignificant, but probably not greater than the uncertainty

Effect of higher degree loading on seasonal geocenter from SLR



More realistic error estimates based on 2x formal errors

X (amp)	X (phase)	Y (amp)	Y (phase)	Z (amp)	Z (phase)
2.7	39	2.8	321	5.5	28
0.4	10	0.4	8	0.8	14

Summary

- Most reasonable geodetic and model estimates agree well in phase and for the amplitude of Y
- For X and Z, GPS-based and model estimates tend to be smaller than SLR estimates (SLR estimates all agree very well)
- Error probably limited by effects of local site loading, which is relatively small for SLR stations
  - SLR naturally tends to be at benign mid-latitude locations
- Annual geocenter motion could be included as a conventional model (for operational altimeter orbit determination, for example), but not necessarily a Class-1 model for analysis
  - Conventional model already includes tidally coherent geocenter
  - Evidence of semi-annual geocenter motion is weak; estimates vary wildly

Afterword

Can long-term geocenter motion provide constraints on ice-mass loss?

Linear term is absorbed into definition of TRF, but accelerations would remain

Comparison of Z geocenter with time series of vertical motion at KELY, Greenland(multiplied by -0.2)

(mass loss in Greenland would move geocenter towards –Z and result in uplift at KELY)